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Donna Wieting, Chief
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Dear Ms. Weiting:

I hereby submit the attached 22 page document entitled "Air-space Resonances and Other Mechanisms Which May Cause Tissue Damage in Cetaceans". The purpose of this document is 'to provide NMFS with background information regarding the Navy's application for a small take permit which would effectively permit the Navy to place it's LFA sonar system into routine operation.

As stated in the preface of the attachment document, I submitted related papers to NMFS at the recent hearing on LFAS in Honolulu. Those papers are now to be considered obsolete and are to be replaced with the attached document. It includes all pertinent information contained in those papers plus additional information.

I am mailing the document today so that it will meet the NMFS imposed deadline. However, tomorrow I intend to fax you an additional much shorter document which will point out why LFAS is an almost non-workable system and a waste of taxpayers money. This should counteract the Navy's argument that LFAS is required for national security.

Sincerely,

Lee Tepley

Lee Tepley, PhD, Physics.

Air-space Resonances and Other Mechanisms Which May Cause Tissue Damage in Cetaceans

by Lee Tepley, PhD, Physics
Update completed on 5-30-01

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Preface

This paper will be submitted to NMFS for the record. as part of my comments on the Navy's application for a small take permit. The Navy's application, if granted by NMFS, will effectively permit LFAS to go into routine operation.

This paper is an update of an earlier paper of the same name which was submitted to NMFS at the hearing in Honolulu on April 28, 2001). This updated version includes the following new results:

1. This paper emphasizes similarities between air-space resonances produced by mid-frequency and low-frequency active sonar (LFAS). Although LFAS was probably not involved in the Bahamas strandings, it is demonstrated below that air-space resonances could cause tissue damage to some of the larger sinus cavities of cetaceans in the same manner as attributed to mid-frequency sonar in the Bahamas case. In addition, air-space resonances produced by LFAS could cause tissue damage to the lungs of many cetaceans. Furthermore, the displacements associated with LFAS induced air-space resonances would be substantially larger than displacements associated with mid-frequency sonar resonances - thus enhancing the likelihood of severe tissue damage. In addition, although the Navy might be able to argue against the mechanism discussed below for resonances in cetacean sinus and middle ear air-spaces caused by mid-frequency sonar, it would be extremely difficult to argue against air-space resonances in the cetacean lung caused by LFA sonar. In fact, the existence of low frequency sound induced air-space resonances in the human lung have already lbeen demonstrated experimentally (Reference 14).

2. This paper points out the possibility of an interaction between an LFAS produced resonance in the cetacean lung or in the ptergoid sinus and a resonance at the same frequency of the tympanic bone of the middle ear. The oscillating tympanic bone could produce an air-space oscillation in the middle ear of comparable amplitude to that produced by an air space resonance.

This paper also discusses possible injury to cetaceans associated with two other possible mechanisms as follows: (1) LFAS induced panic and subsequent problems with equalization and (2) Possible LFAS caused embolisms produced by bubbles in blood vessels.

It is conceivable that a number of the above mechanisms could occur synergistically. An intriguing scenario would be that of a Cuvier Beaked whale moving upwards through the water column and, at about 500 meters depth, suffering an LFAS lung air-space resonance which couples to the middle ear via a tympanic bone resonance. At this point the whale panics and endures severe sinus pain due to problems in equalizing as it bolts towards the surface. Then, at a depth of about 60 meters it suffers a ptergoid sinus air-space resonance at the same LFAS frequency. This resonance again couples into the middle ear via the typmpanic bone resonance. By the time the whale reaches the surface, it has suffered a "multiple whammy". No wonder it sometimes ends up on the beach!! But none of this has been conclusively proven. 'Therefore the Navy can say "no problem". Nevertheless, it is interesting to speculate that something similar could have caused the Beaked whale

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strandings in the Ionean Sea in 1996 where both low and mid-frequency active sonars were employed in NATO tests.

Finally, this paper points out what seems to be a serious misunderstanding on the part of NMFS personnel who cannot understand that "the effective source level" of LFAS really is 240 dB.

This paper modifies and incorporates pe'rtinent information from an earlier paper called "Possible Mechanisms for Strandings of Beaked Whales". That paper - which was also submitted for the record at the NMFS hearing on LFAS in Honolulu - is now obsolete.

A large part of this paper is concerned with air-space resonances - both at mid and LFA sonar frequencies. This is mostly because there is enough information on these resonances to allow a quantitative treatment which, although imperfect, may at least give some idea of what is really happening.. Nevertheless, it should be emphasized that the two other mechanisms considered in this paper could be equally important in causing or contributing to serious injury to cetaceans.

The Navy has either barely considered or totally ignored all of the mechanisms mentioned above and considered below in some detail. It should have been required to thoroughly investigate all of them before even applying to NMFS for a permit which would effectively make LFAS fully operational. In fact, NMFS should insist that the Navy conduct such an investigation and submit a supplementary DEIS to replace the totally inadequate DEIS submitted earlier.

Introduction

The purpose of this paper is to consider a number of mechanisms involving mid and low frequency active sonars which could possibly lead to injury and death of cetaceans. Although 1 have been interested in the possibility of LFAS induced injury to marine life for some time, the effort directly leading to this paper began with the strandings and deaths of beaked whales and other cetaceans in the Bahamas on March 15, 2000.

Following Ken Balcomb's first letter to MARMAM (Reference 2) shortly after the strandings and the Navy's admission that mid-frequency sonar was being employed in the vicinity of the strandings on the day that they occurred, I begin looking into the possibility that a build-up of the sound level in the middle ear due to a Minneart (or air-space) resonance might have caused the strandings,

I soon learned that researchers in the field of cetacean hearing do not yet have a clear picture of what is really happening in the cetacean ear. In addition, not having a background in biology, I had difficulty understanding the complex and contradictory discussions in the scientific literature on the subject. In summary, it turned out to be a lot tougher job than I anticipated.

Nevertheless, I was able to come up with a model that showed that a mid-frequency sonar resonance could increase the sound level in the middle ear air space by about 20 dB. In a recent informal discussion with Dr. Kurt Fristrup, who is under contract to the Navy, he stated that Navy scientists had come up with the same result.. I would not want to misquote Dr. Fristrup but I believe that he also stated that this result would not apply to LFAS because of the difference in frequency ranges between the two sonars. Certainly Joe Johnson has made statements to this effect (as discussed in Section II, Part 2)

In this paper I have extended air-space resonance results to the LFAS frequency range and, came up the same 20 dB increase in sound level. However, in the case of LFAS, the air-space resonances are more likely to be in the larger lung air-spaces rather than the smaller air spaces of the middle ear and sinus cavities. (An important exception, as pointed out by Balcomb, is the possibility of an LFAS resonance in the relatively large ptergoid sinus cavity of the: Cuvier Beaked whale). My results suggest that the 180 dB sound level that the Navy considers safe should at least be replaced by a sound level of 160 dB. Furthermore. there is a lot of data that the Navy continues to ignore that suggests that there is danger to cetaceans at sound levels considerably below 160 dB.

It is possible that mechanisms other than air-space resonances caused or contributed to the strandings and deaths of the cetaceans in the Bahamas (and earlier in the Ionean sea) and that identical or similar mechanisms could cause death to cetaceans at LFAS frequencies. The important point is that many cetaceans are dead for reasons which are not understood.

The results presented below are based largely on my efforts during the past 2 years. Recently, Dr. Michael Hyson and I have been collaborating on this problem. Our discussions have greatly increased my understanding of the mechanisms involved in cetacean hearing. Nevertheless, our resources are quite limited and the results below are still preliminary. In contrast, the Navy has almost unlimited resources. I believe that it should be the Navy's responsibility to thoroughly understand what caused the strandings and deaths in the Bahamas and how these strandings might be related to LFAS before putting LFAS into operation and exposing cetaceans to presently unknown dangers. In contrast, the Navy's attitude seems to be that unless there is absolute proof that LFAS is harmful to cetaceans, it is safe to assume that it is not harmful. **This is a totally illogical and unscientific attitude.**

SECTION I. Air Space Resonances In Sinus Cavities And The Middle Ear Cavity

Introduction

This part of the paper is mostly concerned with supplementing information recently submitted by Ken Balcomb to MARMAM and to the Navy (Reference 1). Balcomb's comments concern the importance of air-space resonance effects which can intensify sound waves from liow and mid frequency active sonars. These sonars are probably responsible for the strandings and deaths of cetaceans in the Bahamas on March 15, 2000 and in the Mediterranean sea in 1996.

Since the Navy is anxious to deploy LFAS, it will probably minimize, ignore or try to debunk the importance of Balcomb's comments on air-space resonances (Reference I). It will probably take the same approach to the following material.

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Until completing the Final Environmental Impact Statement (FEIS) on SURTASS LFA Sonar, I don't think the Navy even acknowledged the possible existence of any resonance effects in cetaceans. Hlowever, in Comment 4-4.15 of the FEIS (in response to a question by Balcomb) the Navy acknowledged the effect while, at the same time, attempting to minimize it's importance. The navy's comment included a statement to the effect that the potential resonance frequency would last for only about 10 seconds which would not be a long enough time to cause any damage to marine mammals. Also, in a press release, Joe Johnson stated: "It takes a fairly steady tone to create resonance". These two comments seem to make no sense. As discussed in SECTION VI near the end of this paper, it would take only a few milliseconds for the sound wave pressure to build up to a dangerously high level for both mid and LFA sonar frequencies. In 10 seconds the marine mammal could be hit by several thousand cycles of the sound wave at a pressure at or near the resonance pressure.

After reading an earlier message by Balcomb and Claridge posted on MARMAM (Reference 2), I spent a great deal of time investigating the possibility of the Minneart resonance intensifying sound waves from mid-frequency sonars. I posted the results on my web site in a long technical paper. Some of those results were based on a model of the cetacean middle ear which I now consider incorrect. Other results have been modified and incorporated into this paper. I did not otherwise publicize my early results because I had some doubts as to whether the air-space resonance would be strong enough to cause damage to cetaceans as suggested by Balcomb and Claridge. However, in view of Balcomb's recent comments (Reference 1) and in view of the results presented below, it seems likely that a sonar sound level of 160 dB (or less) is strong enough to cause serious injury to cetaceans. Therefore, the Navy should not be permitted to arbitrarily state that any sound level below 180 dB is relatively safe.

Balcomb demonstrated in Reference 1 that an air space resonance could occur at reasonable depths at both mid and LFAS sonar frequencies in the ptergoid sinus cavity of a beaked whale. However, he did not calculate the actual pressure increases and displacements in air spaces associated with the resonances. Calculations of this type are presented below.

PART 1: Mathematical Formulation

The first mathematical formulation for the air-space resonance was done by Minneart in 1933 (Reference 4). He considered an air bubble oscillating (expanding and contracting) in open water. This effect was investigated in more detail by Devin in 1959 (Reference 5). Both investigations lead to the same equation which turned out to be identical in form to an equation considered in almost all college classes in physics and in electric circuit theory. Hence, the results are well known and can be easily applied. A related problem - the resonance of an air bubble in a fish bladder - was formulated and solved by Andreeva. His original paper was published in Russian and, apparently, was never translated to English. However, a summary and application of his results was translated to English in 1964 (Reference 6). In deep water the Minneart and Andreeva resonances lead to almost identical results. In shallow water the results diverge because the Andreeva results take into account the elasticity of the tissue surrounding the air bubble (the fish bladder). In deep water tissue elasticity has only a very small effect.

I assume below that Minneart's and Andreeva's equations can be applied to the case of' an air bubble restricted to an air space in a cetacean and separated from open water by the cetacean's bone and tissue (Minneart's equation is used whenever possible because it is simpler). In PART 6 below, I present arguments to justify this assumption.

PART 2: Pressure Build-Up At Resonance

The pressure build-up produced by the Minneart (air space) resonance for a bubble oscillating in open water is given by the ratio of the sound pressure at the resonance frequency to the sound pressure at a much lower frequency. The latter sound pressure tends toward a constant value as the sound frequency approaches zero as shown in **Figure** 3. 'The ratio of the two pressures turns out to be equal to a quantity usually referred to in electric circuit theory as "the Figure of Merit", "the Q factor" or as just plain "Q". The greater the value of Q, the sharper the resonance and the greater the increase in sound pressure. In an air space of a marine mammal, the value of Q is limited by sound absorption in adjacent tissues and can only be estimated, One way of estimating the value of Q is to consider the case of the resonance of an air bubble oscillating in water. It was calculated by Devin to be Q = 25 for frequencies in the range of mid-frequency sonar. In this paper I use a value of Q = 10. This happens to be about the same value of Q that is given by Andreeva (Reference 6) which, in the case of the oscillation of a fish bladder, is independent of frequency. This means that the sound pressure would be increased by the same factor of 10 which is equivalent to 20 dB. Although this is a relatively small increase, it suggests that the level of 180 dB - which even the Navy admits is on the verge of being dangerous - should be replaced by 160 dB. There is a great deal of data already available to the effect that sound levels even lower than 160 dB are dangerous but the Navy has made a great effort to minimize the importance of such data.. However, the demonstrated importance of the Mineral (air-space) resonance should make it more difficult for the Navy to continue this charade.

PART 3: Frequency Of Air-Space Resonance

The Mineral resonance frequency of a bubble oscillating in deep water depends only on the ambient pressure and the mean radius of the bubble which decreases with increasing depth as the ambient pressure increases. This is taken into account using Boil's law. In Part 6 below, it is argued that the air spaces of cetaceans will oscillate in the same manner as does a free bubble in open water.

Having no knowledge of the actual air-space volumes of any cetaceans, I calculated the depths at which the Mineral resonance would occur for a series of air-space volumes that seemed reasonable. The applicable equations are given in **Figure 1**. The results are given in **Figure** 2. Balcomb followed the same procedure in Reference 1 to calculate the air-space resonance frequency for the Ptergoid sac of a beaked whale at the sonar mid-frequency of 3500 Hz . Since the air space of the Ptergoid sac is larger than that of the middle ear, the resonance occurred at a greater depth..

PART 4. Amplitude Of Air Space Resonance Oscillation:

The amplitude of the air-space resonance oscillation - often referred to as the "displacement" - can be calculated from the equation of motion of an oscillating bubble. This equation is given in **Figure 1** and was taken from my earlier paper (now obsolete). The results in **Figure 2** are based on a Q factor of 10 and a sound level of 160 dB in the water next to the air bubble. It is also assumed that half of the energy of the sound wave enters the air bubble which leads to a sound level of 157 dB in the air space of the middle ear or sinus cavity. Finally, the r.m.s. displacement of the sound wave is converted to peak-to-peak since this leads to the back and forth displacement which would be related to tissue damage.

The displacements at resonance were found to be in the range 0.5 to I .4 microns peak-to-peak. 1 had expected to find larger oscillations and was surprised to find that they were in the microscopic range. Initially, this caused me to question the importance of the Minneart resonance effect. 'The Navy could also use this fact to argue against it's importance. Therefore, I think it is crucial to demonstrate that a small oscillation is sufficient to cause a very large and dangerous effect.

A. First, it follows from basic physics that the displacement will be small. This is because the pressure in the air-space is initially the same as the pressure of the surrounding water. Than the air-space bubble is caused to oscillate (expand and contract) by a sound wave which has propagated through the water by rapidly increasing and decreasing the ambient water pressure. At the water's surface, the ambient water pressure is 1 atmosphere (the same as the air pressure at the surface). Perhaps surprisingly, this is equivalent to 220 dB. As we go deeper the water pressure increases. At 100 atmospheres (3,200 ft down), the ambient pressure has increased to 260 dB. But even just below the surface the ambient pressure is far greater than the sound wave pressure unless the air-space bubble is extremely close to the sonar source. Hence the bubble is being caused to oscillate by only a small perturbation in the ambient water pressure. For example, consider a 160 dB sound wave. This is a very intense sound wave but at 100 atmospheres the ambient water pressure is about 100,000 times greater. Since the perturbation is small, the displacement will also bc small. Although the displacement is increased at resonance by the Q factor it will still be small because the ambient pressure will be far greater than the sound wave pressure (except very close to the sound source).

B. Although a displacement on the order of a micron - which would be expected in the cetacean middle ear and sinus air spaces - is in the microscopic range, it will be demonstrated below that it may be large enough to cause tissue damage to cetaceans. This is because we are dealing with the effects of damage to tissues and cells which are also microscopically small objects.

Furthermore., if we consider an air space that can resonate at both mid and LFAS sonar frequencies, the displacement (and subsequent tissue damage) is likely to be far greater at the LFAS frequency. This is demonstrated in Section 2, PART 2. Hence it can be argued that, under some conditions, tissue damage at LFAS frequencies may far exceed middle ear and sinus damage at sonar mid-frequencies.

The relatively large ptergoid cavity of a beaked whale is an example of such a cavity. It's volume is such that it can resonate at both mid and LFA sonar frequencies at different depths. Using Minneart's equation, Balcomb calculated a resonance depth of 1400 meters (Reference I). Using the same equation, a resonance depth of 74 mctcrs is obtained at the LFAS frequency of 300 Hz. However, at this relatively shallow depth Minneart's equation gives only an approximate result. Using Andreeva's equation a resonance depth of *about* 60 mctcrs is obtained assuming a value of 10^6 dynes/cm^2 for the shear modulus. (The significance of the "shear modulus" is discussed briefly in SECTION 2, Part 2). This result is included in the table in **Figure 4.**

The displacement at the mid-frequency air-space resonance of the ptergoid sinus for a 160 dB sound wave is about 0.5 micron as shown in the table in **Figure 2.** However, as discussed in Section **2,** PART **2, the displacement of this sinus air space at any LFAS frequency will be much greater**

The equations and table in **Figure** 2 also demonstrate a rather curious and counter-intuitive result; that is, the displacement produced by an air space resonance decreases as the surface voiume of the air space increases. This is because the resonance occurs at a greater depth for an air space which is larger at the surface. This result is also shown in Section II, Part 2.

PART 5: Resonance Oscillations And Tissue Damage In The Middle Ear

1 can barely recall taking a biology course in high school so the Navy does not have to challenge my expertise in biology because I don't have any. Nevertheless, from a biology textbook (courtesy of Duane Erway) and from a quick search of the web, I obtained values of from 1 to 10 microns for the width of blood cells and 10 microns for the width of epithelial cells in the human intestine. The latter may be similar to the epithelial cells that make up the erectile tissue which contains blood and partially surrounds the air spaces in the heads of cetaceans. The function of this erectile tissue is discussed in SECTION III.

So for the case of mid-frequency sonar we are dealing with a situation where cells of about 1- 10 microns across are being hit repetitively by a sound wave of about 1 micron peak-to-peak amplitude. The sound wave could distort an initially round cell into something resembling a pancake. 'Would the cell then be ruptured?? This might be a good place for a microbiologist to weigh in but, to my simple mind, the result could easily be severe tissue damage. Air-space resonance oscillations must be taken very seriously. They explain why a 160 dB sound wave could be more than adequate to injure cetaceans and lead to bleeding. strandings, disorientation and, ultimately to death.

PART 6. Argument For Occurrence Of Air-Space Resonance In A Cavity Surrounded By Bone And Tissue

The above discussion assumes that the air-space resonance that occurs in a bubble in open water would occur in the same manner in air cavities of cetaceans. The Navy might argue that the concept of an air-space resonance would not apply to sinus or middle ear cavities in cetaceans because these cavities arc mostly surrounded by bone. However, as discussed below. this turns out not to be the case.

First, some background on the conditions necessary for an air-space resonance.
As discussed earlier, the same equations apply to the resonance of a free bubble oscillating in water as to other well known resonance effects in physics and electric circuit theory. However, there is a significant difference. For example, resonance effects in organ pipes, on violin strings, in microwave ovens, etc., occur when half the wavelength is the same as

a critical dimension of the object. This permits the formation of a "standing wave" and a build-up of stored energy.

This is not the case for the resonance of an oscillating bubble. In fact, at both mid and LFA sonar frequencies., the wavelength of the sound wave is much longer than the diameter of the bubble and the concept of "standing waves" does not apply. In fact, in approaching this problem mathematically, it is not necessary to specifically consider sound waves propagating through the water surrounding the bubble. Instead, it is only necessary to consider an alternating water pressure (actually due to the passing sound wave) which is uniform all around the bubble. When the water pressure increases, the bubble is compressed (or contracted) and stores energy. When the water pressure is reversed, the bubble expands and radiates the energy it has just absorbed. At a certain frequency - called "The Minneart frequency" - the bubble resonates and the oscillation amplitude increases as discussed earlier..

The concepts of "contraction" and "expansion" are vital if a "bubble resonance" or an "airspace resonance" in a cavity is to occur. In contrast, if a bubble in open water were replaced by a hollow rigid air-filled sphere, there would be no resonance effect. It is easy to show that very little sound energy would penetrate the sphere. Almost all the energy would be reflected..

Similarly, if a middle ear or sinus cavity were rigid, there could be no air-space resonance. Until recently, 1 thought that such cavities were inside the skull and likely to be fairly rigid.. However, Dr. Michael Hyson was able to obtain an excellent book by Dr. Gerald Fleischer entitled "Evolutionary Principles of the Matntnalian Middle Ear" (Reference 12). Although the book was published in 1978, it does not seem to be well known among whale researchers. In any cause Dr. Hyson (who was a close associate of Dr. Fleischer) and myself have been studying the book and related papers by Dr. Fleischer. It is clear that both middle car and sinus cavities are outside the skull and, as we interpret Dr. Fleischer's work, the air cavities of all cetaceans are likely to be quite flexible for the following reasons.

I. Althourgh roughly 1/3 of the middle car cavity is up against the ptergoid bone which is extremely rigid, the remaining walls of the cavity are surrounded by either the tympanic bone or by soft tissue which couples the cavity to the outside water. The tissue has about the same acoustic impedance as water and is likely to be quite flexibie. Thus, pressure changes in the water are likely to be conducted into the middle ear cavity through the tissue with little or no absorption.

2. The tympanic bone is also likely to be quite flexible. In fact, Fleischer argues that vibrations of this bone couple sound to the input of the inner ear via the ossicle chain. Also, the tympanic bone is separated from the ouside water by soft tissue. Thus, pressure changes in the water are conducted through the tissue either directly to the middle ear cavity or indirectly through the tissue to the tympanic bone . Dr. Fleischer also argues that the tympanic bone is like to have a mechanical resonance of several hundred cycles for dolphins and at a lower frequency for the larger baleen whales. This resonance effect will be discussed further in PART 7.

The above arguments seems to be consistent with the views of Dr. Darlene Ketten who is one of the few recognized authorities on cetacean ears. She believes that low frequency sounds are conducted to the middle ear primarily through non-rigid fatty tissues (References 8 and 9). This is consistent with our interpretation of Dr. Fleischer's work.

In summary, Dr. Hyson and myself interpret Dr. Fleischer's work as being consistent with the idea that tissue surrounding the air spaces in the middle ear and sinuses of cetaceans is flexible and can expand and contract in much the same way as does a bubble oscillating in open water. It follows that air-space resonances would occur. However, if the tissues should turn out to be extremely rigid, air-space resonances would either not occur or would be of low amplitude in the middle ear and sinuses of cetaceans, **However, it is likely that the tisssue surrounding cetacean lungs is extremely flexible. Hence, it can be argued that, even if resonances do not occur in in middle ear and sinus air spaces of cetaceans, they would be quite likely to occur in cetacean lung air spaces. It has already been demonstrated that they occur in the air spaces of the human lung (Reference 14).**

SECTION II: Possible Resonances At LFAS Frequencies.

PART 1: Low Frequency Mechanical Resonance Of The Tympanic Bone In The Middle Ear Cavity.

An important part of Dr. Fleischer's intriguing model is his prediction that the hearing sensitivity curve of cetaceans - as shown in audiograms - is largely determined by a series of cascading mechanical resonances of the tympanic bone, the malleus-incus complex and the stapes. Of particular interest in regard to possible LFAS effects is the mechanical resonance of the tytnpanic bone which is much larger and heavier than the other bones and which therefore would resonate at a much lower frequency. Although it would be extremely difficult to calculate it's resonance frequency for any species of cetacean, Dr. Fleischer believes that it would occur at about several hundred Hz. for dolphins and at somewhat lower frequencies for the larger cetaceans.

It is known that the tympanic bone encloses a large part of the middle ear cavity. Therefore, it is conceivable that the resonance vibration of the tympanic bone at several hundred Hz. could cause the air in the cavity to contract and expand in a manner similar to that discussed above for an air-space resonance which would occur at a much higher frequency. Nevertheless, the possibility exists for tissue damage in the middle ear due to a low frequency resonance vibration of the tympanic bone.

Furthermore, there is a possibility that energy from an LFAS lung resonance (discussed in PART 2 immediately below) will couple into the middle ear resonance of the tympanic bone and greatly increase it's vibration amplitude. This could significantly increase the possibility of tissue damage in the middle ear because of the increase in contraction and expansion of the air space

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PART 2: LFAS Air Space Resonances

A. Resonance depth and frequency: Except in shallow water, air-space resonance frequencies can be calculated by combining Minneart's equation and Boyle's law. The resultant equation can be written in different ways as shown in **Figures 1 and 2.** A useful way of writing the combined equation is:

$$n = n_R = \left(\frac{f_R R_S}{\mathbf{326}}\right)^{1.2}$$

Where n_R is the depth at which resonance occurs in atmospheres, f_R is the resonant frequency in Hz and R_S is the a radius of the air space in cm. at the surface of the water. This equation shows that, for a given frequency, the larger air spaces will resonate at greater deptlhs. The equation also shows that, for a given air space volume, the lower frequencies will resonate in shallower water. (However, in very shallow water, the above equation is not valid and Andreeva's equation must be used instead. A similar result is obtained but the depth at which resonance occurs will be less.)

In addition, the above equation shows that, at a given depth, a larger air space will resonate at a lower frequency. Hence, in general, a large cavity - such as the lung - is more likely to resonate at an LFAS frequency than a small air space- such as the middle ear. The latter air space is more likely to resonate to the sound wave from mid-frequency sonar.

This leads us to recent statements by Joe Johnson. He has, in effect, stated the following:

1. LFAS was not employed in the Bahamas at the time the strandings occurred.

2. Therefore the Bahama strandings arc irrelevant to any discussion of potential dangers of LFAS.

The first statement may well be correct although Birch has pointed out (Reference 13) that the mid-frequency sonar used in the Bahamas has the capability to operate at LFAS frequencies. **The follow-up statement is clearly misleading** (as are many of Joe Johnson's remarks,). It should be obvious from this paper that resonances in both cetacean lung and large sinus cavities could easily occur at LFAS frequencies. Furthermore, as shown in Item C below, resonant displacements at LFAS frequencies will be substantially greater than those at the higher frequencies of mid-frequency sonar.

13. Examples of LFAS resonances for both cetaceans and humans.

I. Cuvicr beaked whale: The lung air-space resonance would occur a! about ,500 meters for the LFAS mid--band frequency of 300 Hz. The ptergoid sinus resonance would occur at about 60 meters for the same frequency. Thus, as already pointed out in the preface to this paper, a beaked whale moving through the water column could encounter both resonances at different depths. Furthermore both resonances could couple to a tympanic bone resonance in the middle ear at the same frequency. Thus a single LFAS frequency has the potential to cause tissue damage in three separate air spaces. Furthermore, as discussed below, **the displacements caused by the LFAS resonances will be larger than resonances produced by mid-frequency sonar..**

2. Bottlenose dolphin: The lung air-space resonance would occur at about 113 meters at the same LFAS frequency. This depth range arises from the application of Andreeva's equation which is required because the resonance occurs in relatively shallow water. Andreeva'a equation - originally derived to predict air-space resonances of fish bladders - incorporates a quantity called the "shear modulus" which relates to the elasticity of the tissue surrounding the fish bladder. In his paper (Reference 6) Andreeva provided numerical values for the shear modulus which vary by a factor of 10. However, observations of sound waves re-radiated from fish bladders apparently favor the lower value of 10^6 dynes/cm.^{2} which was mostly used by Andreeva and by other workers who have applied his equation. The lower value of the shear modulus was also used by Dr. Michael Hyson to calculate the resonance depths in table 4.

3. Female free diver: The value of the shear modulus which seems to apply to fish may not necessarily apply to the prediction of a lung resonance frequency in a dolphin or a human. However, using the lower value of the shear modulus of 10^6 dynes/cm.^{2} and a lung volume of 4.6 liters in .Andreeva's equation, resonance frequencies of about 44 Hz. and 59 Hz. are obtained at the surface and at 20 ft. depth respectively. This is in dose agreement with experiment (Reference 14) which strongly implies that the lower value of the Shear modulus applies as closely to the tissue around the human lung as it does to tissue around a fish bladder.

Since the calculated resonant frequencies are below the stated LFAS band of 100 -500 Hz., we cannot use a lung air-space resonance to explain the cause of the trauma suffered by a female diver named Chris Reid during the 1996 LFAS tests in Hawaii. It is, of course, conceivable that the Navy was operating LFAS at a lower frequency than stated on the day that Chris Reid was injured.

4. Male scuba diver. Again using a value for the shear modulus of 10^6 dynes/cm.^{2} and a lung volume of 6 liters, Andreeva's equation gives a resonance frequency of 141 hz. at a depth of SO ft. At greater depths the resonant frequency will be higher. Hence LFAS could pose a serious threat to scuba divers.

C. Displacements associated with LFAS resonances: The above examples are concerned only with the resonant frequency of the lung air space. It will now be shown that, under some conditions, the potential for tissue damage will be far greater at LFAS frequencies then at the mid-range sonar frequency of 3500 Hz.

The equation for the displacement, AR, of the air space at the Minneart resonance is given in both figures 1 and 2. It shows that for a given frequency, the displacement decreases with increasing depth. After converting the sound wave pressure from r.m.s. to peak-to-peak, the equation may be rewritten in the following form:

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$$\Delta R = \frac{Q\, P_f\, (2780)}{P_a\, f_R^{1.6} R_s^{0.6}}$$

The above equation shows that for a given air-space surface volutne (and radius), the displacement is greater at a lower frequency.

It can be useful to (compare displacements produced by the same sound wave at different frequencies for air spaces of different radii. From the above equation it can easily be shown that

$$\Delta R_1/\Delta R_2 = (f_{R2}/f_{R1})^{1.6}\ (R_{,,}\ /R_{S1})^{0.6}$$

For the case of the ptergoid sinus of the beaked whale as discussed by Balcomb, the above equation sitnplifics to:

$$\Delta R_1/\Delta R_2 = (f_{R2}/f_{R1})^{1.6}$$

Taking f_{R1} as 300 hz. (the LFAS mid-band frequency) and taking f_{R2} as 3500 hz. for mid-frequency sonar, we obtain:

$$(f_{R2}/f_{R1})^{1.6} = 51$$

Therefore $\Delta R_1 = 51\,\Delta R_2 = 51\,(0.5) = 25.5$ microns. Since this is a much larger displacement than that produced by mid frequency sonar, the potential for tissue damage would be far greater. However, this result may be considered as only an upper limit because it is based on the applicability of the Minneart equation. Although this equation should apply very closely to the deep water (1400 meters) mid-frequency sonar air-space resonance of the ptergoid sac, it will not apply to the relatively shallow water (68 meters) resonance at the LFAS frequency of 300 Hz.. Andreeva's equation would be required in this case. However, since Andreeva's original derivation was in Russian and, apparently, was never translated to English, I do not have access to his equation of motion for an oscillating bubble. Therefore, 1 cannot write Andreeva type equations analogous to those above. Nevertheless, it can be argued that although the displacement at the LFAS mid-band frequency will probably be substantially less than 25 microns, it may well exceed IO microns - far more than enough to cause tissue damage to cetaceans.

Furthermore, the lung resonance of a Cuvier beaked whale at the LFAS mid-band frequency of 300 Hz. occurs in deep enough water so that Minneart's equation should rigorously apply. In this case, the displacement at resonance turns out to be about 6.7 microns. Since-the resonance displacements at LFAS are typically significantly greater than displacements produced by mid-frequency sonar., the potential for tissue damage is also significantly greater.

In addition, energy from the lung and ptergoid sinus air-space resonances could be re-radiated into the middle ear to stimulate a tympmanic bone mechanical resonance which could lead to tissue damage in the middle car. The potential for this "coupled resonance" was discussed briefly in SECTION 1, PART 7.

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Finally, it should be pointed out that mid-frequency sonar (at 3000 Hz.) and LFA sonar (at 600 Hz.) were both used in the NATO tests in the Mediterranean sea in 1996 that resulted in a massive stranding of beaked whales. As they moved upwards or downwards through the water column, they could have encountered both LFA resonances of both the lung and the ptergoid sac at different depths. It is conceivable that energy from these resonances could have been coupled to a tympanic bone resonance of the middle ear. Panic induced by the loud sounds could have resulted in sinus equalization problems (as discussed in the next section). This could have added to the tissue damage cause by the LFA resonances. In addition the whales might have been exposed to almost simultaneous middle ear resonances from the mid-frequency sonar. With all these things happening either simultaneously or in quick succession, it may not seem surprising that a mass stranding occurred. On the other hand NATO and the US Navy argued that there was no proof that high intensity sonars had anything to do with the strandings. Take your choice!!

SECTION III: An Alternative Mechanism - Injury Caused by Panic And Equalization Problems

In late February of 2001, I sent out several e-mails on an alternative mechanism which could have caused the Bahamas strandings, This was before I realized that a relatively small resonance oscillation could cause serious tissue damage as discussed above. Although it now seems that air-space resonances may be extremely important, other mechanisms should not be ruled out. In fact, several mechanisms could work simultaneously to enhance tissue damage.

My alternative mechanism considered the possibility of tissue damage in the middle ear resulting indirectly from the loud sonar sounds which caused cetaceans to become frightened. It has been known for some time that loud sounds sometimes cause cetaceans to panic. In fact, (as pointed out by Duane Erway) "After WWII the Norwegians used sonar to hunt whales because they found the sonar frightened especially baleen whales and caused a predictable flight response making them easier to catch" (this may be a direct quote from Reference 10).

Furthermore, "panic" was the most common explanation offered for the strandings of the beaked whales in the Ionean sea. In that case, no necropsies were obtained so no ear damage was demonstrated. So how can panic be connected to ear damage?? It comes down to the length of the time lag in the cetacean mechanism for "equalization".

As part of every day living, cetaceans dive deep and fast and also ascend rapidly from deep water. It is agreed by all experts that all cetaceans have air-filled sinus and middle ear cavities. To prevent serious car damage, the inside air must rapidly achieve the same pressure as the outside water. This is called "equalization". Human free or scuba divers must also equalize as they descend and ascend. If they do not, the result is intense pain, bleeding around the ear, broken eardrums and, on rare occasions, death.

Most human divers arc familiar with the mechanism for equalization. 1 won't go in to it here. What is important is that cetaceans use an entirely different mechanism because they have to cope with far greater and more rapid changes in water pressure than do human divers. The cetacean mechanism involves blood flowing rapidly in and out of porous tissues which partly surround and extend into the air-filled middle ear and sinus cavities. The porous tissue is thought to closely resemble the erectile tissue of the human male. As the cetacean descends, the tissue engorges with blood causing the cavities to become smaller and the air pressure to increase rapidly to that of the external water pressure. When the cetacean ascends the reverse process occurs.

The above is a pretty amazing mechanism but all the experts seem to agree that it really happens. But there has to be a limit as to how rapidly equalization can occur. If the cetacean should panic and descend or ascend too rapidly, equalization tnight not occur fast enough to totally prevent large differences between air and water pressure. This would cause pain, tissue damage and bleeding which could disorient the cetacean and lead to stranding and death. Under ordinary conditions cetaceans should know how rapidly they can safely descend and ascend. But being panicked by a high energy sound wave is not an ordinary condition.

There may be many other ways in which a malfunction in the equalization mechanism may be related to panic. Four examples follow.

a. Perhaps damage to the crectile tissues in the middle ear caused by an airspace resonance deactivates the equalization mechanism.

b. Perhaps panic effects, the cetacean's nervous system is a manner that causes the equalization mechanism to malfunction - even if the cetacean is not ascending or descending extremely fast.

c. Perhaps the equalization mechanism may not work; well in older or sickly cetaceans. Then panic- resulting in a rapid ascent or descent - could make the situation worse.

d. Perhaps ocean pollution has lead to toxins in the cetacean diet which has affected blood circulation of even young healthy cetaceans. This could cause or aggravate equalization problems.

The Navy and NMFS should not arbitrarily 'dismiss mechanisms involving equalization problems associated with panic simply because they have not been proven. The fact is that whales have been killed by mid-frequency sonar.

Panic might be more likely for the smaller cetaceans at higher frequencies - like those of mid frequency sonar - where they are likely to have higher hearing sensitivity - but it could be equally likely for the larger cetaceans at LFAS frequencies - especially for the baleen whales who have high hearing sensitivity in the LFAS frequency range.

SECTION IV. Another Alternative Mechanism - Bleeding Caused By Bubbles In The Blood And Tissue

Crum and Mao (Reference 1 1) have investigated the problem of sound waves enhancing the growth of bubbles in blood for both humans and marine mammals under a number of conditions. The mechanism involved is called "rectified diffusion". They showed (as acknowledged by the Navy in the FEIS) that significant bubble growth may occur at sound levels above 190 dB. This would ordinarily occur only if a cetacean was very close to the sonar source. However, in a private communication to me, Dr. Crum stated that, under conditions of extreme super-saturation, bubbles might possibly occur at substantially lower sound levels; but this situation has not been investigated. Conditions of extreme super-saturation would occur for cetaceans - such as sperm whales or beaked whales that can remain at great depths for long periods of time. **-Bubbles in blood vessels can lead to embolisms and bleeding. An air-space resonance would increase the sound level in the air space and, as a consequence, increase the probability of bubbles forming in blood vessels near the air space.**

SECTION V: The "240 dB" Effective Source Level for LFAS

ln a phone conversation between Mark Palmer of the Earth island Institute and Dr. Roger Gentry of NMFS, Dr. Gentry apparently stated that the proposed LFA level was 215 dB. The exact quote from Mark's message is "The Navy is also claiming that the Bahamas sonar was used at 230 dB, higher than the LFA level of 215 dB."

It is discouraging that the 215 dB number keeps coming up over and over again. It is incorrect and Dr. Gentry should know better. 215 dB refers to the output of a single element of the LFA array. Since there are 18 elements, the effective output is about 240 dB.

The concept of an "'effective output" or "an effective source level" is important when comparing outputs and (distant sound levels from different sources. This is exactly what Dr. Gentry did above and, because he does not understand the concept of "effective source level", he did it wrong - or, perhaps, he was mislead by the Navy.

I spent some time trying to explain the concept of effective source level in earlier e-mails but it is difficult to understand for anyone without a technical background and my efforts never seem to take hold. I won't make another effort here because this message is already quite long. However, I will again point out that the 25 dB difference between 2.15 dB and 240 dB is given by the formula 25 dB = 20 log (18 squared). This is even admitted by the Navy (but very quietly) on Page B-3 of the appendix of the draft DEIS.

Also, in my comments on the DEIS I brought this point up again. In reply the Navy briefly mentioned the term "effective source level" but it dodged my question by not specifically stating it was 240 dB. It appears that the Navy's policy is to be deliberately misleading - perhaps to prevent people like Dr. Gentry from becoming overly concerned. This is upsetting because NMFS will determine if and when LFAS goes operational. 'I'hercfore NMFS personnel should be required to understand the technicalities about LFAS but apparently they do not. Hence, NMFS will probably go along with the Navy's propaganda.

One final comment on the effective source level: It is probably correct that the actual sound level close to the LFAS cable does not exceed 215 dB but this is of little importance because, as pointed out in Part 9 above, if a cetacean is close enough to the cable so that it encounters a sound level of greater than 190 dB, it is likely to be seriously injured because bubbles will have formed in it's blood vessels. Therefore, it may not make much difference if a cetacean comes any closer. What is far more important is that the effective source level be used when considering and comparing the effects of LFAS and other sonars in the so-called "far field" - that is, at distances greater than 1 kilometer from the source. The LFAS sound level can sometimes be at a dangerous level of 150 - 160 dB out to several hundred kilometers from the source and therefore, can cause injury or death to very large numbers of cetaceans - even at great distances. In contrast, the Navy's so-called "mitigation measures" (even if they work) would prevent serious injury to an almost negligibly small number of cetaceans which happen to be very near the source. As the saying goes: "Out of sight, out of mind".

SECTION VI: CETACEAN EXPOSURE TIME TO SONAR SIGNALS

As discussed in the Introduction above, the comments about resonance in the FEIS and by Joe Johnson might be interpreted as suggesting that the sound amplitude would not have time to build up to a dangerous value while the sound frequency was in the resonance range. This is incorrect as shown below.

A. BUILD-UP TIME: From the electrical analogue of the Minneart resonance, I was able to derive the complete equation of motion at resonance - including the transient build-up time when the sound wave first strikes the air space. The build-up time depends only on the resonant frequency and the Q of the resonance circuit. I used the value of Q = 10 as discussed above. The equation was a bit complicated but Duane and Jennifer Erway were able to plot the results using computer programs. At 300 Hz - taken as the mid-frequency of LFAS - it took only about 5 cycles for the signal to build up to it's maximum value. This corresponds to about 17 milliseconds. At 3500 Hz. - taken as the frequency of mid-frequency sonar - it again took about 5 cycles. This corresponds to about 1.4 Jnilliseconds. For practical purposes, both build-up times can be considered to be instantaneous.

B. SWEEP-THROUGH TIME: I don't know if mid-frequency sonar sweeps at all. If it does not sweep, the cetacean could bc exposed to the resonance frequency until it swims out of the resonance region. This could take many seconds. For LFAS I again assume a mid frequency of 300 Hz. Taking Q = 10 as before, leads to a bandwidth of 30 Hz. The signal would be 3 dB down at both 285 Hz. and 3 15 Hz. The Navy can vary the LFAS frequency in many different ways. However, it seems to prefer operating LFAS at a constant or slowly varying frequency for from 5 to 10 seconds (Reference 7, Page 34). Then LFAS is abruptly switched to another constant or slowly varying frequency. This Jneans that if the LFAS frequency should coincide with an air-space resonance frequency, the cetacean will bc subject to the same (or a nearby) frequency for from 5 to 10 seconds. The cetacean may be hit by about 2000 oscillations before the frequency is changed. I suspect that only a few oscillations would bc enough to cause damage - but 2000 oscillations?'? How can the FEIS and Joe Johnson imply **"no problem!!"**

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Figure. 1
Equations for an oscillating bubble at resonance

Minneart's Equation for a gas bubble oscillating in water is:

$$f_R = \frac{1}{2\Pi R_R}\sqrt{\frac{3\gamma P_R}{\rho}}\text{, where } \rho = 1 gm/cm^3 \text{ and } \gamma = 1.4$$

Also, $P_R = nP_a$

where $P_a = 10^6\, dynes/cm^2 \longrightarrow 220dB$ = Pressure at one atmosphere

$$\text{Also } V_R = \frac{4}{3}\Pi R_R{}^3,\ V_S = \frac{4}{3}\Pi R_S{}^3, \qquad \frac{V_S}{V_R} = \frac{P_R}{P_a} = n = \left(\frac{R_S}{R_R}\right)^3, \quad R_R = \frac{R_S}{n^{1/3}}$$

After substituting and rearranging, Minneart's equation can be re-written as

$$f_R = \frac{n^{1/3}}{2\Pi R_S}\sqrt{\frac{3\gamma n P_a}{\rho}} = \frac{n^{5/6}}{2\Pi R_S}\sqrt{\frac{3\gamma P_a}{\rho}}$$

Or

$$n = n_R = \left(\frac{f_R R_S}{326}\right)^{1.2} \text{ where } R_S = \left(\frac{3}{4\Pi}V_S\right)^{1/3} = \frac{V_S{}^{1/3}}{1.61}$$

and n_R is the pressure in atmospheres corresponding to the resonance frequency f_R

Also, from the equation of motion of an oscillating bubble at resonance:

$$\frac{AR}{R_R} = \frac{Q}{3\gamma n_R}\frac{P_f}{P_a} \text{ where AR = change of the bubble radius}$$

Substituting and rearranging:

$$\Delta R = \frac{1}{2\Pi f_R}\left(\frac{QP_f}{P_a}\right)\sqrt{\frac{P_a}{3\gamma n_R}} = 77.5\frac{P_f}{P_a}\left(\frac{Q}{f_R\sqrt{n_R}}\right|$$

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Figure 2

Depths And Air Space Volumes For Resonance Of A Free Bubble In Water At 3500 Hz.

The following equations were taken from Figure 1

$$n = n_R = \left(\frac{f_R R_S}{326}\right)^{1.2}, \qquad \Delta R = \frac{1}{2\Pi f_R}\left(\frac{QP_f}{P_a}\right)\sqrt{\frac{P_a}{3\gamma n_R}} = 77.5\frac{P_f}{P_a}\left(\frac{Q}{f_R\sqrt{n_R}}\right)$$

For f_R = 3500 Hz., $Q = 10$, P_f = 157 dB, $P_f / P_a = 1/1400$

V_S (cubic cm.)	R_S (cm.)	n_R (atmospheres)	Depth (ft.)	AK” (microns)
835 (extrapolated from Halcomb's data for ptergoid sinus	5.84	143.6	4592	0.37
160	3.37	74.44	2350	0.50
80	2.68	56.26	1768	0.59
40	2.124	42.10`	1347	0..68
20	1.69	32.46	1007	0.77
10	1.34	24.6	755	0.89
5	1.06	18.73	567	1.02
1	0.62	9.78	281	1.4

*The numbers in this column were obtained from the above formuln for A R except that a multiplier of 2.8 was employed to convert the sound wave pressure from r.m.s. to peak-to peak. This should relate more directly to possible tissue damage.

Figure 3
Series of "Q" Curves to Illustrate Sharpness of Resonance

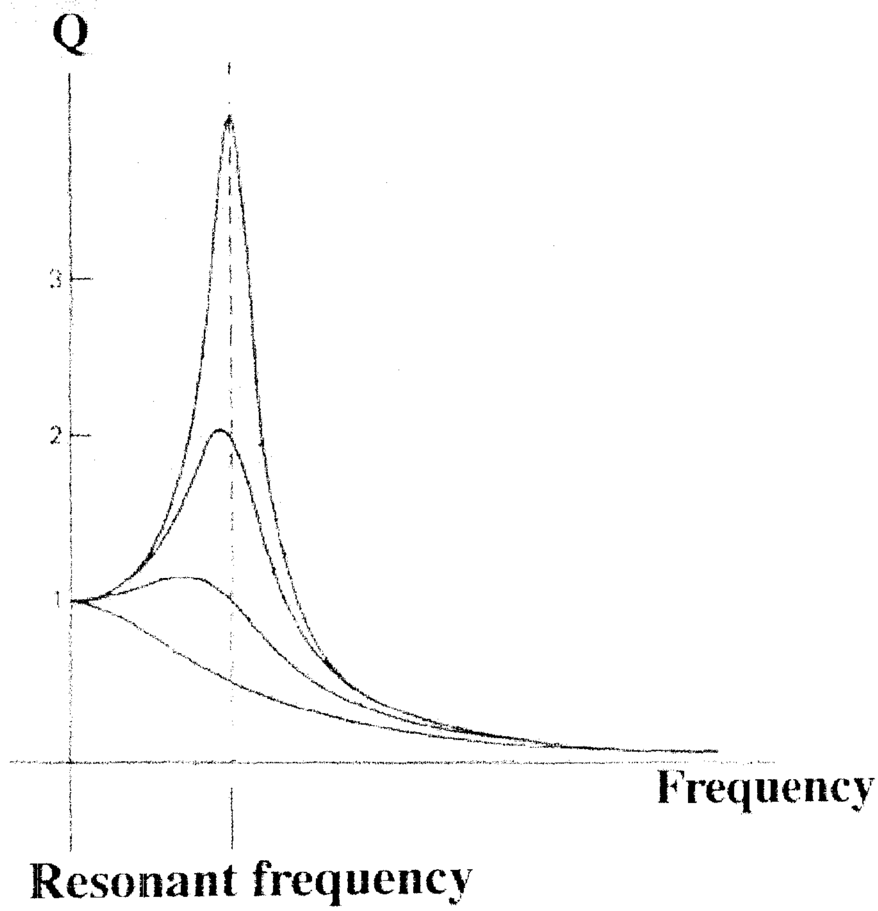

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Figure 4
Resonance Depths at LFAS Frequencies

Source	Air Space	Air-space surface volume	Resonance depth at 3 LFAS frequencies calculated from Andreeva's equation* by Michael Hyson using a computer program.		
			100 hz	300 hz	500 hz.
Saclanlcen Report	Finback lung	2000 liters	438 meters	1647 meters	3042 meters
Saclantcen Keport	Bottlenose lung	3.25 liters	9.5 meters	113 meters	2 12 meters
Saclantcen Report	Beaked whale lung	136 liters	137.5 meters	556 meters	1039 meters
Extrapolated from Balcomb's letter	Beaked whale ptergoid sinus	0.84 liters	5.4 meters	59.5 meters	122.4 meters

*The above results were obtained using a value for the Shear Modulus of 10^6 dynes/cm^2